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Integration of a Fire Detector into a Spacecraft

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A detector sensitive to only the ultraviolet radiation emitted by flames has been selected as the basic element of the NASA Skylab fire detection system. It is sensitive to approximately 10^{-12}W of radiation and will detect small flames at distances in excess of 3m. The performance of the detector was verified by experiments in an aircraft flying zero-gravity parabolas to simulate the characteristics of a fire which the detector must sense. Extensive investigation and exacting design was necessary to exclude all possible sources of false alarms. Optical measurements were made on all the spacecraft windows to determine the amount of solar radiation transmitted. The lighting systems and the onboard experiments also were appraised for ultraviolet emissions. Proton-accelerator tests were performed to determine the interaction of the Earth's trapped radiation belts with the detectors and the design of the instrument was modified to negate these effects.

Introduction

ALTHOUGH fire detectors have been deployed in commercial and military aircraft for some years, the NASA Skylab will be the first U.S. space vehicle to be equipped with a fire detection system. The Apollo spacecraft fire emphasized the need for such systems and the NASA Fire Hazard Steering Committee initiated preliminary developments in this area.

This paper describes the development of the Skylab fire detection sensor and the experiments undertaken to verify its capabilities. The rationale for the selection of an ultraviolet detector is described and a description of the detector tube is included. Experiments on zero-gravity combustion, proton radiation effects and the ultraviolet radiation background are also discussed.

Selection of the Ultraviolet Sensor

The fire detection systems that were considered for the Skylab included the devices listed in Table 1. For this particular application any device that would rely on sampling the cabin atmosphere was rejected as the Skylab air circulation could delay the response of such systems with disastrous consequences. Sampling detectors were also eliminated because of their inability to identify the exact location of a fire. Correlation spectrometer/interferometers are being developed to scan large volumes, but the development program for such an instrument was incompatible with the Skylab launch schedule. Continuous wire thermistors are used extensively to sense fires in aircraft-engine nacelles. An extremely complicated network of thermistor or thermocouples would have been required for adequate coverage of the Skylab system. Infrared detectors have often been used in spacecraft optical systems but are relatively unproven for fire detection. Furthermore, they are liable to false alarms from hot objects and are insensitive to low-pressure flames.

All flames emit ultraviolet radiation and extremely sensitive detectors are available for this spectral region. Although these detectors respond only to an open flame, their sensitivity is such that the small flames which they will detect, if extinguished promptly, should not threaten the safety of the Skylab crew. The wavelength range of operation of the ultraviolet

Table 1 Fire-detection devices considered for Skylab

Category	Type of detector	Parameter detected	Comments
Optical	Ultraviolet	UV radiation from flame	Proven; volume surveillance
	Infrared	IR radiation from fire	Unproven; volume surveillance
Chemical	Laser scattering	Smoke	Required development; sampling
	Correlation spectrometer	Gaseous combustion products	Required development; sampling
	Condensation nuclei counter	Smoke	Frequent maintenance; sampling
	Ion counter	Smoke	Liable to false alarm; sampling
Thermal	Continuous wire thermistor	Heat	Requires complicated wiring for volume coverage
	Thermocouple	Heat	Requires complicated wiring for volume coverage
Physical	Pressure	Increase in cabin pressure	Very insensitive

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Index categories: Manned Space Station Systems; Spacecraft Habitability and Life Support Systems.

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detectors is below 300 nm; therefore, they are "blind" to most of the background radiation sources in the Skylab, such as the lights, the crew, scientific instruments, and, for the most part, the solar radiation penetrating the spacecraft windows. False alarms cannot be tolerated, so this lack of response to background sources was an influencing factor in the final choice of the ultraviolet detectors. These detectors have been widely used in fire detector systems for aircraft, on launch pads, in automotive systems, in heating systems, and in many experimental facilities.

Ultraviolet Detector Tube

The tube is of the Geiger-Mueller type[1] and consists of two parallel plate electrodes in a gas-filled, ultraviolet-transmitting glass envelope. Ultraviolet radiation incident upon the tube releases photoelectrons from the metal cathode triggering an avalanche ionization process. Each time this ionization is triggered by an incident ultraviolet photon, the conductivity of the tube rises rapidy, and a voltage pulse is generated at the output. The frequency of these pulses is used to indicate the presence of a fire.

Only photons of a certain minimum energy (maximum wavelength) will liberate electrons from the photocathode. With the metallic cathode material used in the Honeywell detector the upper wavelength limit is about 260 nm, while absorption of radiation by atmospheric oxygen results in a 180 nm lower limit. A typical calibration curve for one of these sensors is shown in Fig. 1, in which the countrate per unit energy density (counts sec^{-1} picowatt^{-1} cm^{2}) is plotted against the wavelength. This curve demonstrates the sensitivity of the sensor. In the 190–240 nm range approximately 50 counts are generated by 1 picowatt cm^{-2} of incident radiation. Although the quantum efficiency of the cathode at these wavelengths is on the order of 0.01%, the avalanche mechanism ensures that a high percentage of the liberated electrons is detected. Furthermore, the number of false counts due to thermal activation and background visible radiation is essentially zero. Few quantitative measurements have been made of the spectral radiance of fires at these wavelengths

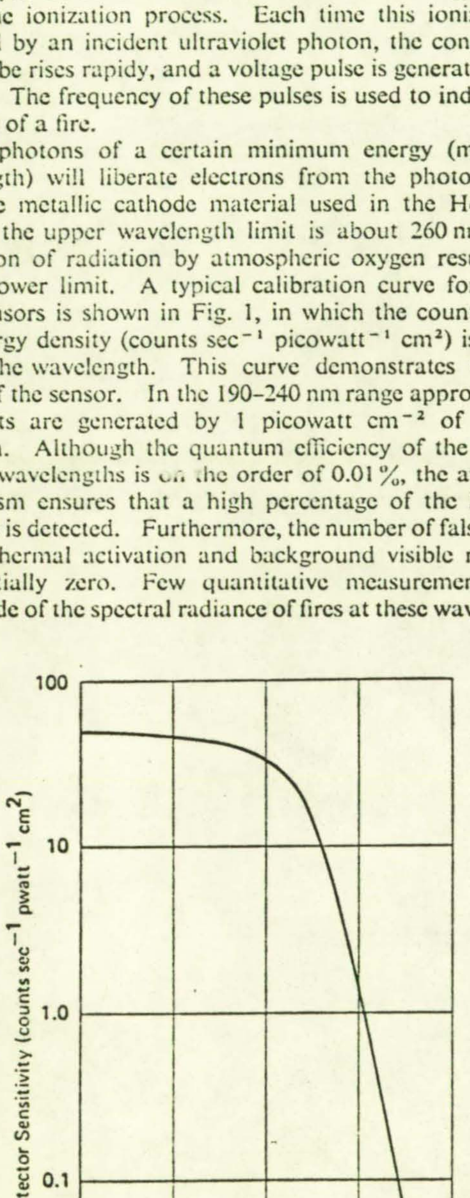

Fig. 1 Spectral calibration of the Honeywell fire-detector tube.

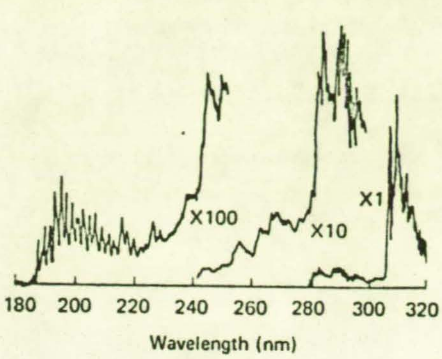

Fig. 2 Spectrometer output during scan of a methane/air flame. (Figure reproduced by permission of Honeywell, Inc.)

but the curve in Fig. 2 is representative of many hydrocarbon fires. Molecular emissions are apparent in the 185–260 nm band, but these are two orders of magnitude less intense than the familiar 306.8 nm OH bands. Such weak emissions must be detected by the fire sensors across the large volumes of the Orbital Workshop module of the Skylab. In such extreme situations, the fire could be further than 3 m from the nearest possible sensor installation; however, the ultraviolet detector tube has been proven to be more than adequate for the task.

Detection Capability

An alarm threshold had to be established for the Skylab detectors. This threshold determined the sensitivity of the detection system, or, more importantly, the size to which a flame must grow before it could be detected. Moreover, the threshold had to be set high enough to preclude the incidence of false alarms.

A prediction of the detection capability from the known spectral calibration curve of the detector tube was rendered impossible by a complete lack of spectral radiance data for fires at applicable wavelengths. Further, any such data obtained in the laboratory under normal gravitational conditions would inadequately represent a fire burning in the low-pressure, oxygen-rich, zero-gravity environment of the Skylab. Convection currents are established around Earth-bound fires maintaining supplies of fresh oxygen to the flames; under zero-gravity condition there will be no natural convection around the flame, and fires can be expected to burn less fiercely.[2,3] Some convection will be maintained by the Skylab ventilation systems in the crew-living areas but several of the fire detectors will monitor enclosed compartments through which air is not circulated.

To evaluate the performance of the Skylab detector, a series of experiments was undertaken in which a detector tube

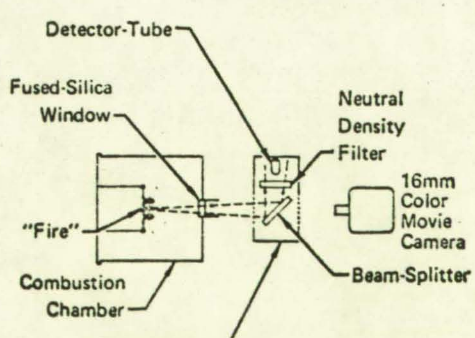

Fig. 3 Combustion chamber and optical transfer system for the zero-gravity experiments.

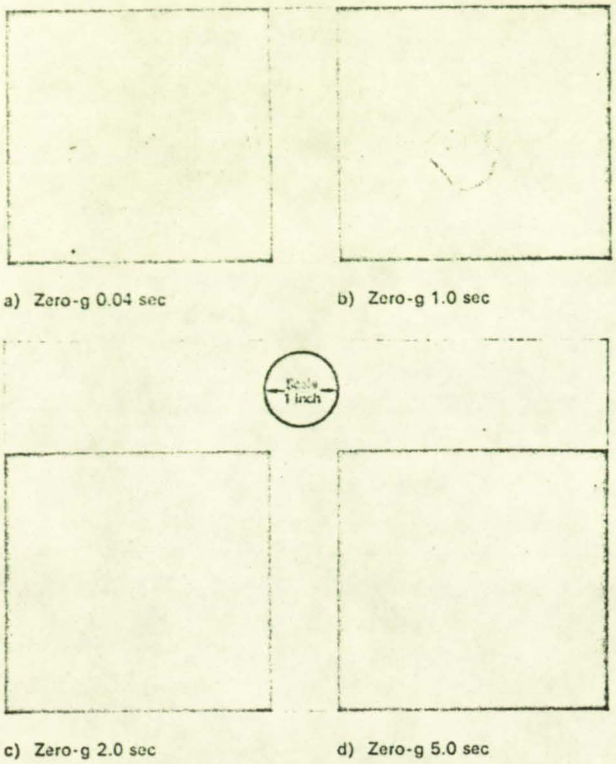

Fig. 4 Combustion of photographic film in zero-gravity.

monitored various small fires burning in zero-gravity.[4] Small samples of a wide variety of spacecraft materials were burned in a combustion chamber filled with the 5 psi oxygen-nitrogen atmosphere of the Skylab. Two detector tubes were installed so that they viewed the fires through the transfer optics illustrated in Fig. 3, as the combustion was recorded on 16 mm color movie film. The neutral filter was installed to attenuate the radiation and thus simulate a 3 m fire-to-detector separation.

To generate the weightless environment, the chamber was released to free-float in the cabin of an USAF C-135 aircraft flying a parabolic trajectory. During this maneuver 15 or 20 sec of free-float time was available.

Examples of the photographs and data obtained during the experiments are illustrated in Figs. 4 and 5. The flame photographs illustrate the unique characteristics of zero-gravity flames: the spherical flame growth and the self-extinction of the fires by the combustion products. Detector-output curves emphasize the brief nature of the fire compared with a one-gravity burn. Nevertheless, the signals generated in the detector tubes during every combustion cycle studied, significantly exceeded 35 counts/sec. This level was subsequently selected as the alarm threshold after the false alarm studies described below. Throughout the experiments, not one of the flames exceeded 4 cm in diam, and yet they all would have been detected from 3 m, within a second or two of ignition.

Prevention of False Alarms

Detection of a fire which could threaten the safety of the Skylab crew or the integrity of the vehicle is of prime importance. However, a system that developed frequent false alarms would cause severe problems for the crew and it might even have to be deactivated. Inevitably, a sensitive device is always susceptible to false alarms unless the alarm-threshold is set suitably high. To establish the minimum level a thorough study of the spacecraft environment was undertaken and its effect on the fire sensor was assessed.

Ultraviolet Radiation

As the ultraviolet fire detector is sensitive to picowatts of emitted radiation, extreme care had to be taken to ensure that even very weak background radiation sources were eliminated. The sun is the prime source of such radiation, but spacecraft lighting, photographic lighting, scientific experiments, and electrostatic discharges are among other possible sources of ultraviolet photons. Statistical computations showed that the maximum background irradiance that can be tolerated at the sensor location is 10^{-14}w cm^{-2}, if the occurrence of false alarms is to be less than one per 56-day mission.

Solar radiation outside the spacecraft includes approximately 4×10^{-4}w cm^{-2} in the sensitivity range of the fire sensor, and data from the OGO IV ultraviolet spectrometer indicates that even the Earth's albedo is rich in ultraviolet radiation[5] (Fig. 6). Various window materials are used in the Skylab: fused silica, Vycor, Corning ≠1723 aluminosilicate glass, and Ohara ≠BK7 borosilicate glass. Fused silica and Vycor both transmit a high percentage of incident ultraviolet radiation, and spacecraft windows constructed with these materials have had to be coated with reflective and absorbing films. Blue reflective coatings have been utilized, but antireflection coatings and certain environmental control coatings, deposited to meet other optical requirements, also were found to reduce the ultraviolet intensity by several orders of magnitude. Borosilicate and aluminosilicate glasses are often thought of as "opaque" in the middle ultraviolet, but transmission curves for one of the Airlock module window elements (Fig. 7) show that the use of quotation marks is justified. In the range of interest, below 270nm, the ≠7913 aluminosilicate element would transmit 0.001% of the energy

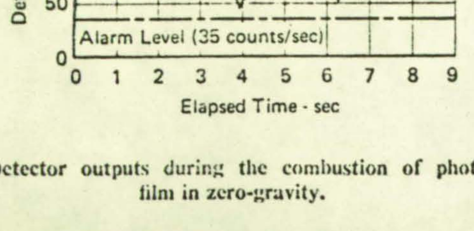

Fig. 5 Detector outputs during the combustion of photographic film in zero-gravity.

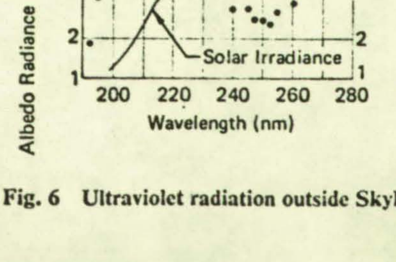

Fig. 6 Ultraviolet radiation outside Skylab.

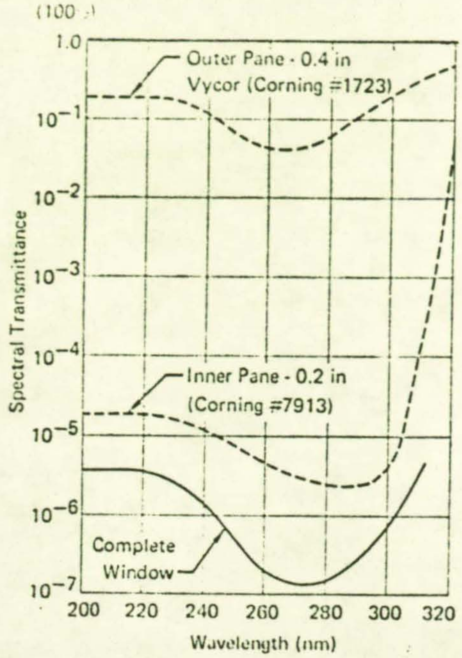

Fig. 7 Spectral transmittance of the Skylab STS window elements.

and the assembled window would attenuate direct solar radiation by only six orders or magnitude. However, as ten or eleven orders were needed to prevent false alarms, this window also had to be coated with an attenuating coating.

Mercury vapor fluorescent lamps are used widely in the Skylab modules, and it was feared that the strong 253.7nm mercury emission line would trigger the detector. However, measurements showed that the glass envelope effectively absorbs all the ultraviolet radiation. The experiments to be performed by the crew and the photographic lighting were also shown to make an insignificant contribution to the ultraviolet background.

The time constants of the detection circuit were selected so that static discharges will not trigger the alarm system. Lastly, the interior surfaces of the Skylab have been studied, and, as their ultraviolet reflectivity is less than 10%, the radiation absorbed by these surfaces will further reduce the risk of false alarms.

Particulate Radiation

During certain orbits, the Skylab will pass through the South Atlantic Anomaly in the trapped radiation belts around the Earth. Energetic protons and electrons, oscillating along spiral paths between the magnetic poles, will intersect some five or six of the daily orbits. The resultant proton fluxes inside the spacecraft were calculated for such orbits, with a computer program based on published data.[6] Profiles for the most intense fluxes are illustrated in Fig. 8

Electrons and protons impinging on the detector tube will cause ionization of the gas between the electrodes of the tube. The free electrons produced will be indistinguishable from photoelectrons, gas avalanches will occur, and pulses will be generated in the detector circuits. The electron energies are such that a thin layer of fused silica would easily shield the sensor against these particles. On the other hand, the proton energies range up to 200 Mev. Experiments on the NASA Langley proton synchrocyclotron confirmed that the proton fluxes would generate frequent false alarms because any shielding configuration of acceptable weight would still allow the countrate to exceed 150 counts per sec. The alarm threshold could have been set above this level, but the performance of the device would have been degraded for the

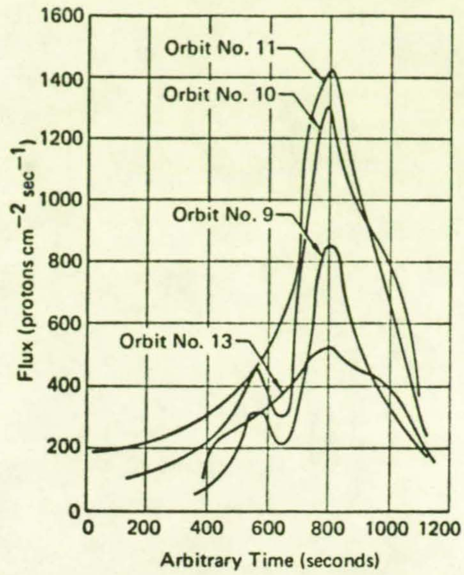

Fig. 8 Predicted proton fluxes inside Skylab during passage through the South Atlantic anomaly.

whole mission, while the high-flux rates will only be experienced for less than 5% of the time.

To overcome this problem, a "twin tube" concept was developed. One tube will monitor ultraviolet radiation and will also be exposed to the proton environment and a second "blind" tube will detect only the background proton fluxes. The outputs from these sensors, when fed into differential circuits, will generate a signal in proportion to the intensity of the ultraviolet radiation only.

Even with the twin tube arrangement, some shielding is necessary to reduce the background signals in the detection circuits. The diagram of the proposed design in Fig. 9 shows the combination of fused silica and copper shielding which will exclude protons less energetic than 85 Mev.

A statistical analysis of the design, based on estimates of the particulate fluxes in the Skylab orbit, has indicated that a threshold of 35 counts per sec, and a time constant of one second, will preclude more than one false alarm for each 56-day mission. The zero-gravity experiments verified that a detector with these settings would be sensitive to very small fires ignited up to 3m away.

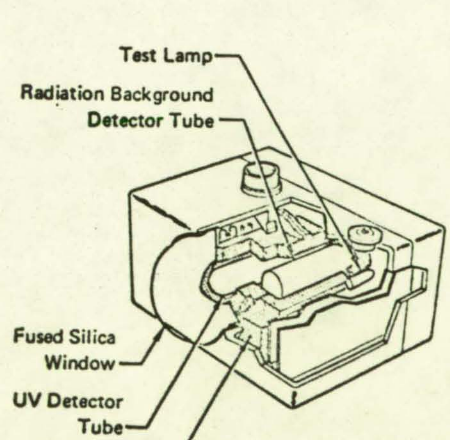

Fig. 9 The Skylab fire detector. (Figure reproduced by permission of Honeywell, Inc.)

Skylab Fire-Detection System

Flight-worthy fire sensors are now in production and a system of 22 sensors is being installed in the component modules of the Skylab. The locations of the units were selected on the basis of a survey of the combustible material throughout the Skylab and the unlikely prospect of an ignition source nearby. Wherever possible the sensors have been installed so that there is overlap between the 120° field-of-view of neighboring units. Crew living and working areas, storage areas, instrument panels, cooling and life support systems will all be monitored. Should a small fire be ignited anywhere inside the Skylab, it will quickly be detected and located so that prompt action can be taken.

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